THE ASTROPHYSICAL JOURNAL, 347:915–924, 1989 December 15

LOW-FREQUENCY OBSERVATIONS OF GALACTIC SUPERNOVA REMNANTS AND THE DISTRIBUTION OF LOW-DENSITY IONIZED GAS IN THE INTERSTELLAR MEDIUM

NAMIR E. KASSIM[1]
Astronomy Program, University of Maryland, and E. O. Hulburt Center for Space Research, Naval Research Laboratory
Received 1989 February 14; accepted 1989 June 15

ABSTRACT

New long-wavelength observations of Galactic supernova remnants (SNRs) at 30.9 and 57.5 MHz are used to derive detailed low-frequency radio spectra for 32 SNRs. Of these, approximately two-thirds show turnovers at low frequencies, implying the presence of a widespread, but inhomogeneous, ionized absorbing medium along the lines of sight. These observations are combined with other low-frequency data to derive free-free optical depths toward 47 SNRs and to constrain the physical properties of the ionized gas responsible for the absorption. Three generally accepted ionized components of the interstellar medium (ISM) which absorb low-frequency radio emission are (1) H II regions; (2) extended H II region envelopes (EHEs); and (3) the warm ionized medium (WIM). The absence of absorption toward some distant SNRs places an upper limit on the thermal electron density (n_e) of a widely distributed WIM of $n_e \leq 0.26$ cm^{-3} for an assumed electron temperature of $T_e = 8000$ K (case 3). Absorption by small, normal H II regions or planetary nebulae located near to or along the lines of sight to the SNRs (case 1) cannot be ruled out, but the derived optical depths are consistent with the expected absorbing properties of EHEs (case 2) first inferred from 325 MHz recombination line observations. Such EHEs, if present, have $T_e \sim 3000$–8000 K, $n_e \sim 0.5$–10 cm^{-3}, and sizes of 50–200 pc, and comparison of centimeter-to-meter wavelength recombination line data suggests that they are probably associated with "classical" H II regions. If the EHEs are common, they may be an intermediate ISM component between H II regions and the WIM, although their volume filling factor in the Galaxy is small ($\leq 1\%$).

Subject headings: interstellar: matter — nebulae: H II regions — nebulae: supernova remnants — radio sources: spectra

I. INTRODUCTION

Many supernova remnants (SNRs) have well-determined radio spectra at centimeter wavelengths which almost invariably appear to have a constant index α ($S \propto \nu^{+\alpha}$) over the entire radio range. Only a few cases (e.g., the SNRs W49 [Holden and Caswell 1969], 3C 391 [Caswell *et al.* 1971], and Sgr A East [Dulk and Slee 1972]) show significant deviations from the constant spectral index known at frequencies ≥ 100 MHz, and these "turnovers" are attributed to absorption by dense ($n_e \geq 10$ cm^{-3}) thermal gas along the line of sight. In general, observations below 100 MHz are required to detect turnovers due to absorption by hot, lower density ionized gas, and in the past observations at such frequencies have had such poor resolution that they have not permitted the study of the spectra of individual sources. An exception is the classic work of Dulk and Slee (1972, 1975), who observed a number of Galactic SNRs at 80 MHz using the Culgoora radioheliograph. While many of these SNRs show spectral turnovers, their results are imprecise, since the turnover frequency is often very near their lowest observing frequency of 80 MHz. (The Culgoora results are discussed in more detail in §§ III and IV*a*.)

Now, for the first time, we are able to extend information on the spectra of a significant number of SNRs down to dekameter wavelengths and find that many, but not all, show clear turnovers at $\nu \approx 100$ MHz even though there are no obvious intervening thermal sources along the line of sight. From these new data, we are able to place limits on the properties and distribution of several of the ionized components of the interstellar medium (ISM).

[1] National Research Council/NRL Cooperative Research Associate.

There are at present several generally accepted ionized components of the ISM, whose filling factors are all poorly known. In order of increasing electron density n_e, these include: (1) the hot interstellar medium (HIM) with electron temperature $T_e \sim 10^6$ K, $n_e \sim 10^{-3}$ cm^{-3}; (2) the warm ionized medium (WIM) with $T_e \sim 8000$ K, $n_e \sim 0.1$ cm^{-3}; (3) postulated halos of ionized gas surrounding normal H II regions (extended H II envelopes; hereafter EHEs) with $T_e \sim 5000$ K, $n_e \sim 5$ cm^{-3}; and (4) normal H II regions with $T_e \sim 5000$ K, $n_e \geq 50$ cm^{-3}. The HIM is transparent even to very low-frequency continuum radio emission, so we have no further information on it. Also, information on the physical properties of normal H II regions from low-frequency observations has been discussed elsewhere (Odegard 1986*a*, *b*; Kassim 1987; Kassim and Weiler 1989; Kassim *et al.* 1989). From the present data, we are able to provide limits on the properties of the WIM and an estimate of the distribution and properties of the EHEs.

a) The Warm Ionized Medium (WIM)

Evidence for a warm ionized medium (WIM) component of the ISM is based largely on work by Reynolds (1983, 1984, 1988, and references therein), who has observed the optical metastable lines of O II and N II superposed upon a widespread, diffuse Hα emission-line background. If the filling factor of the WIM is large, it is an important component of the ISM because the power required to maintain it is comparable to the total power injected into the ISM by supernovae ($\sim 10^{42}$ ergs s^{-1}; Reynolds 1984), although Mathis (1986) has suggested that the WIM could be ionized by O star photons emerging from H II regions which are not completely radiation bounded.

Estimated properties of the WIM are derived by Kulkarni and Heiles (1987) and are summarized as:

Electron temperature (T_e)	$\sim$3000–8000 K
Electron density (n_e)	$\sim$0.3 cm^{-3}
Fractional ionization	$\geq$0.75, i.e., highly ionized
Filling factor	$\geq$10%.

These numbers are only crude estimates based upon limited information and involve several basic assumptions which may not be valid. For example, it is assumed that the WIM is in pressure equilibrium with the other atomic phases and that its characteristics, derived mainly from observations of local gas, apply to the whole Galaxy. However, they are the best estimates which are available at present for the WIM.

b) Extended H II *Envelopes (EHE)*

High-frequency ($\geq$1 GHz) radio recombination line surveys and moderate- to high-frequency (408 MHz $\leq \nu \leq$ 10 GHz) radio continuum surveys provide information on H II regions (see Wilson 1980, and references therein) but appear to need an additional ionized component of the ISM. These studies mainly detect high-density ($n_e \sim$ 50–1000 cm^{-3}), hot ($T_e \sim$ 5000–10,000 K), "classical" H II regions which appear as discrete sources scattered along the Galactic plane, but also provide some evidence for a more widespread, lower density ionized gas. The so-called "Galactic ridge" recombination lines (hereafter GRRLs) (Gottesman and Gordon 1970; Jackson and Kerr 1975; Lockman 1976; Hart and Pedlar 1976) appeared to originate in areas free of discrete H II regions, but, more recently, H272α (325 MHz) GRRLs detected in a survey conducted with the Ooty radio telescope (Anantharamaiah 1985*a*, *b*, 1986; hereafter A85*a*, A85*b*, A86, respectively) can *only* be produced by low-density ionized gas. Such low-frequency recombination lines are produced by stimulated emission and cannot arise in high-density gas because of opacity and pressure broadening (Shaver 1976). These low-frequency GRRLs have been detected in all directions in the inner Galaxy ($l \leq 40°$), even in the absence of any discrete sources along the line of sight.

The Ooty data (A85*a*), when combined with higher frequency recombination line, continuum, and pulsar dispersion measurements (A85*b*, A86), constrain the properties of the line-emitting gas to be

Electron temperature (T_e)	$\sim$3000–8000 K
Electron density (n_e)	$\sim$0.5–10.0 cm^{-3}
Emission measure (EM)	$\sim$500–3000 cm^{-6} pc^{-1}
Path length (l)	$\sim$50–200 pc
Filling factor	<1%.

The fact that the derived path length is short and the filling factor is low suggests that this gas is not a distributed component of the ISM, but is more likely associated with individual, discrete sources. Anantharamaiah (A85*b*, A86) suggests that "halos" or "envelopes" (which we have designated EHEs) of low-density ionized gas surrounding high-density "classical" H II regions[2] could be the origin, a conclusion based on the agreement between the velocities of the high- and low-density line-emitting regions. However, since the large fan beam of the Ooty telescope (2° × 6′) does not permit unambiguous determination of the source positions, the existence of EHEs needs to be confirmed.

One method of confirming the existence of or at least setting limits on the WIM and the EHEs is through measurement of their absorbing effects on low-frequency radio radiation. Particularly useful is the determination of the low-frequency spectra of SNRs because it is believed, and there is considerable evidence (including data presented in this paper; see § IV*a*), that their spectra are of constant index throughout the radio range. Thus, any low-frequency deviation must be caused by intervening, absorbing gas. Also, the wide distribution of SNRs along the Galactic plane gives a good sampling of the Galactic ridge gas.

II. DATA

Using the low-frequency data on 32 mainly first-quadrant SNRs which fall within the range of the 30.9 MHz Clark Lake Radio Observatory (CLRO; Erickson, Mahoney, and Erb 1982) Galactic Plane Survey (Kassim 1987, 1988*a*; hereafter K87, K88*a*), and 15 higher latitude SNRs mainly toward the outer Galaxy observed in separate Clark Lake studies, we have been able to obtain optical depth measurements for 47 Galactic SNRs. To reduce confusion, a number of the CLRO Galactic Plane Survey sources were reobserved at 57.5 MHz and reduced in a manner identical to that used for the 30.9 MHz data described in K87 and K88*a*.

Table 1 lists all SNRs included in this study by their Galactic coordinate names to the nearest tenth of a degree (as is conventional) and by any other commonly cited names (cols. [1] and [2]), their positions in equatorial (R.A., Decl.; epoch 1950.0) coordinates (cols. [3] and [4]), the best estimates of their angular size (col. [5], in arcminutes), the Clark Lake frequencies at which they have been observed (col. [6]), and references for other low-frequency measurements not included in K87 and K88*a* (col. [7]). All positions and size estimates have been taken from the comprehensive SNR catalog of Green (1984, 1988).

In a separate paper (Kassim 1989; see also K87) we summarize all available flux densities for the 32 SNRs whose spectra are derived in § III below. These include the low-frequency Clark Lake measurements as well as all available higher frequency flux density measurements obtained from the literature. These data are plotted below, along with the derived spectra (Figs. 1*a*–1*d*). In compiling these data, an effort was made to bring all measurements to the absolute flux density scale of Baars *et al.* (1977), and to eliminate poor or inappropriate measurements. Since some personal judgement was needed to do this, *all* available flux densities are listed in Kassim (1989), to which the reader is referred for a complete description of the method by which the data used to derive the spectra were compiled.

III. RESULTS

A spectrum has been derived for each of 32 SNRs from the data listed in Kassim (1989) by a least-squares fit to the equation:

$$S_\nu = [S_{408}(\nu/408)^\alpha] \exp[-\tau_{408}(\nu/408)^{-2.1}] , \qquad (1)$$

where S_ν is the integrated flux density in janskys at frequency ν in MHz, and S_{408} is the flux density at a reference frequency chosen to be 408 MHz. The best-fit spectra, many of which

[2] As noted in A85*b* and A86, the suggestion that H II regions have a core-halo structure is not a new one. Attempts to interpret recombination line to continuum intensities as a function of frequency have always required lower density gas to be associated with the normal H II regions. (See A86, and references therein.)

TABLE 1

SNRs Included in Study

Source (1)	Other Names (2)	R.A. (1950)[a] (3)	Decl.[a] (4)	Size[a] (5)	Clark Lake Frequency (MHz) (6)	Reference[b] (7)
G348.5+0.1	CTB37A	$17^h10^m40^s$	$-38°29'$	10	57.5	1
G348.7+0.3	CTB37B	17 10 30	−38 08	10	57.5	1
G349.7+0.2		17 14 35	−37 23	2.5 × 2.0	57.5	
G350.1−0.3		17 17 40	−37 24	4?	57.5	
G355.9−2.5		17 42 35	−33 42	13	30.9	
G0.0+0.0	Sgr A East	17 42 33	−28 59	3.5 × 2.5	80.0, 110.6	2
G0.9+0.1		17 44 12	−28 08	8	80.0	3
G1.05−0.1[c,d]		17 45 32	−28 06	4.3	80.0	3
G5.4−1.2	Milne 56	17 59 00	−24 55	35	30.9, 57.5	1
G6.4−0.1	W28	17 57 30	−23 25	42	30.9	
G8.7−0.1	W30	18 02 35	−21 25	45	30.9	4
G9.8+0.6		18 02 10	−20 14	12	57.5	
G10.0−0.3		18 05 40	−20 26	8?	57.5	
G11.2−0.3		18 08 30	−19 26	4	30.9, 57.5	
G11.4−0.1		18 07 50	−19 06	8	57.5	
G12.0−0.1		18 09 15	−18 38	5?	30.9	
G15.9+0.2		18 16 00	−15 03	7 × 5	30.9	
G18.8+0.3	Kes 67	18 21 10	−12 25	18 × 13	30.9, 57.5	
G21.5−0.9		18 30 37	−10 37	1.2	30.9, 57.5	
G21.8−0.6	Kes 69	18 30 00	−10 10	20	30.9, 57.5	
G22.7−0.2		18 30 30	−09 15	26	57.5	
G23.3−0.3	W41	18 32 00	−08 50	27	57.5	
G23.6+0.3		18 30 20	−08 15	10?	57.5	
G24.7+0.6		18 31 30	−07 07	30 × 15	30.9	
G24.7−0.6		18 36 00	−07 35	15?	30.9	
G27.4+0.0	Kes 73	18 38 40	−04 59	4	30.9	
G29.7−0.3	Kes 75	18 43 48	−03 02	3	30.9	
G31.9+0.0	3C 391	18 46 50	−00 59	5	30.9	
G32.8−0.1	Kes 78	18 48 50	−00 12	17	30.9	
G33.2−0.6		18 51 12	−00 05	18	30.9	
G33.6+0.1	Kes 79	18 50 15	00 37	10	30.9	
G34.7−0.4	3C 392	18 53 30	01 18	35 × 27	30.9	
G39.2−0.3	3C 396	19 01 40	05 23	8 × 6	30.9	
G40.5−0.5	Flo	19 04 45	06 26	22	30.9	
G41.1−0.3	3C 397	19 05 08	07 03	4.5 × 2.5	26.3, 30.9	
G43.3−0.2	W49B	19 08 44	09 01	4 × 3	30.9	
G46.8−0.3		19 15 50	12 04	17 × 13	30.9	
G54.4−0.3	HC 40	19 31 10	18 50	40	30.9	
G74.0−8.5	Cyg Loop	20 49 00	30 30	230 × 160	40.0	5
G89.0+4.7	HB 21	20 43 30	50 25	120 × 90	40.0	6, 7
G94.0+1.0	3C 434.1	21 23 10	51 40	30 × 25	30.9	
G111.7−2.1	Cas A	23 21 10	58 32	5	16.0–123.0	
G130.7+3.1	3C 58	02 01 55	64 35	9 × 5	57.5	8
G160.9+2.6	HB 9	04 57 00	46 36	140 × 120	25.6	9
G184.6−5.8	Tau A	05 31 30	21 59	7 × 5	25.6–110.6	
G189.1+3.0	IC 433	06 14 00	22 36	45	25.6–73.8	10
G206.9+2.3		06 46 00	06 30	220	25.6–73.8	11
G260.4−3.4	Pup A	08 20 30	−42 50	60 × 50	25.6–73.8	10

[a] From Green 1984, 1988.

[b] (1) Kassim, Weiler, and Baum 1989. (2) Kassim, Erickson, and LaRosa 1986. (3) LaRosa and Kassim 1985. (4) Kassim and Weiler 1989. (5) Jackson, Kassim, and Kundu 1985. (6) Mahoney 1986. (7) Mahoney and Kassim 1985. (8) Reynolds and Aller 1985. (9) Jackson 1985, private communication. (10) Erickson and Mahoney 1985. (11) Odegard 1986*b*. If no reference is given, the low-frequency measurement can be found in Kassim 1987, 1988*a*, 1989.

[c] Not included as an SNR in Green's most recent catalog; Green 1988.

[d] Position and size from Downes *et al.* 1978.

show low-frequency turnovers, are shown in Figures 1*a*–1*d*. The intrinsic spectral index (α) of an SNR is assumed to be constant throughout the radio range, and τ_{408} is the optical depth at the reference frequency. The optical depth at 30.9 MHz ($\tau_{30.9}$) has been derived from τ_{408} through multiplication by the appropriate conversion factor of $(30.9/408)^{-2.1}$. All three derived parameters ($\tau_{30.9}$, α, and S_{408}) are tabulated in Table 2 (cols. [2], [4], and [5], respectively), which lists the SNRs by Galactic coordinate name (col. [1]) and also gives Green's (1988) best estimate of their morphological type (col. [6]) (S, shell; P, plerionic [filled-center or Crab Nebula–like], or C, complex). Table 2 also lists derived optical depths for an additional 15 SNRs obtained from separate Clark Lake studies (mostly with $\tau_{30.9} \ll 1$), for which no spectra were derived. Values of α and S_{408} for these 15 SNRs are reproduced from the Green (1988) catalog.

As expected, $\tau_{30.9}$ is most sensitive to the accuracy of the lowest frequency flux density measurements; i.e., those from Clark Lake, so that the errors for τ have been obtained from the $\sim$20% error estimate appropriate to the Clark Lake data

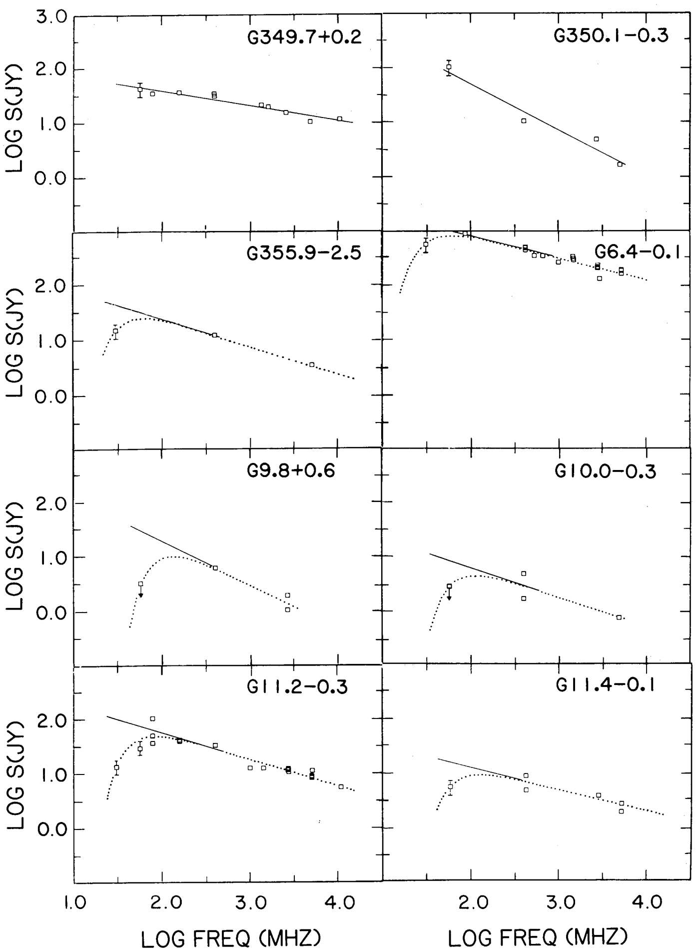

FIG. 1a

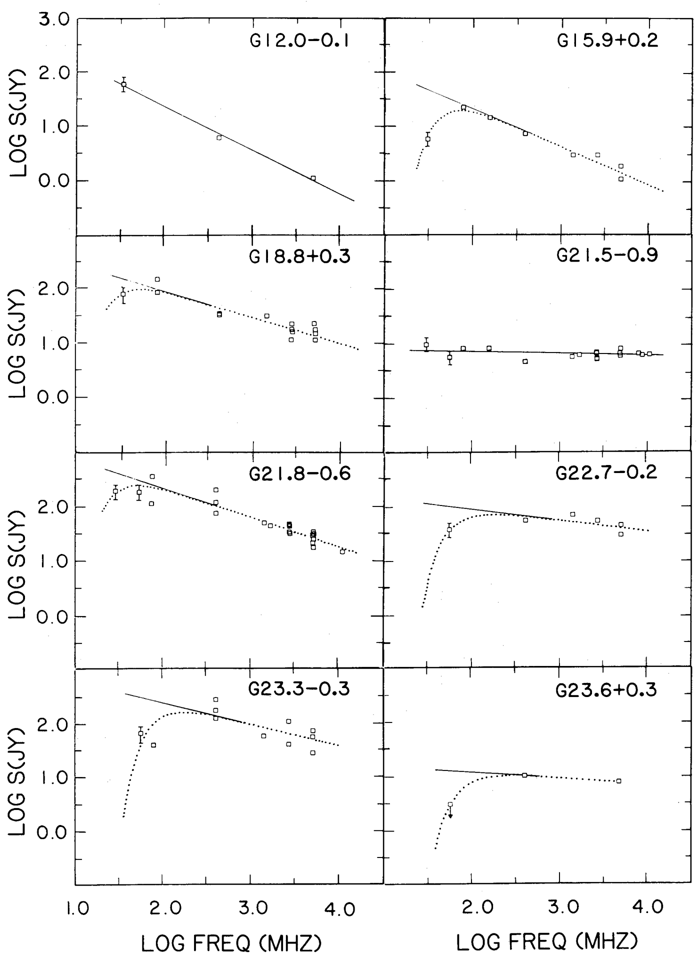

FIG. 1b

FIG. 1.—(*a*)–(*d*): Least-squares fit spectra (eq. [1]) to the flux density values listed in Kassim (1989) for 32 Galactic SNRs. Dotted lines represent the best fit to the available data points which are depicted by square symbols. Solid lines show what the low-frequency portion of the spectrum would be if no absorption were present. Roughly two-thirds of these SNR spectra show evidence for a low-frequency turnover due to absorption by ionized foreground gas.

(K87, K88*a*; see also Kassim 1989). While τ is also dependent on the spectral index of the SNR and therefore on the higher frequency measurements, in most cases numerous higher frequency measurements were available to determine the optically thin spectral index, making τ much less sensitive to the error of any individual measurement. For comparison, Table 2 (col. [3]) also lists the optical depths (scaled to 30.9 MHz) derived by Dulk and Slee (1972, 1975) at 80 MHz for the 13 SNRs included in both studies.

There is reasonable agreement between the Dulk and Slee and the Clark Lake results for all but four sources (G348.5+0.1, G349.7+0.2, G33.7+0.1, G43.3−0.2). In these four cases, the Culgoora result predicts a much higher $\tau_{30.9}$ than is observed. Dramatic examples are G33.7+0.1 and G43.3−0.2, where use of the Culgoora optical depth in equation (1) predicts a 30.9 MHz flux density of ≈ 5 Jy for each source, while values of 94 and 59 Jy, respectively, are measured (K87, K88*a*). The reason for these four discrepancies is undoubtedly the nearness of the inferred turnover frequency to the Culgoora observing frequency of 80 MHz, giving a large error in the estimate of the optical depth.

IV. CONSTRAINTS ON THE PROPERTIES AND DISTRIBUTION OF LOW-DENSITY IONIZED GAS IN THE ISM

a) Validity of SNR Spectra as a Probe of the ISM

To use SNRs and their low-frequency spectral turnovers as a probe of the properties of the low-density, ionized gas in the ISM, we assume that they have intrinsic power-law, nonthermal spectra with constant index (α) down to frequencies below 30.9 MHz, and that any turnovers in their low-frequency spectra are produced by free-free absorption along the line of sight. Dulk and Slee (1972) have already discussed the lack of any theoretical reasons to expect intrinsic turnovers in the low-frequency spectra of SNRs, and our observations lend additional support to this assumption. Nearly all nearby, high-latitude, or outer Galaxy SNRs show no low-frequency turnovers (G111.7−2.1, G130.7+3.1, G160.9+2.6, G184.6−5.8, G189.1+3.0, and G260.4−3.4; Table 2) and many remnants which lie in directions toward the inner Galaxy with relatively little absorption (e.g., G349.7+0.2, G350.1−0.3, G12.0−0.1, G21.5−0.9, G32.8−0.1, G33.2−0.6, G33.6+0.1, G34.7−0.4, G54.4−0.3, and G94.0+1.0; Fig. 1) show straight spectra.

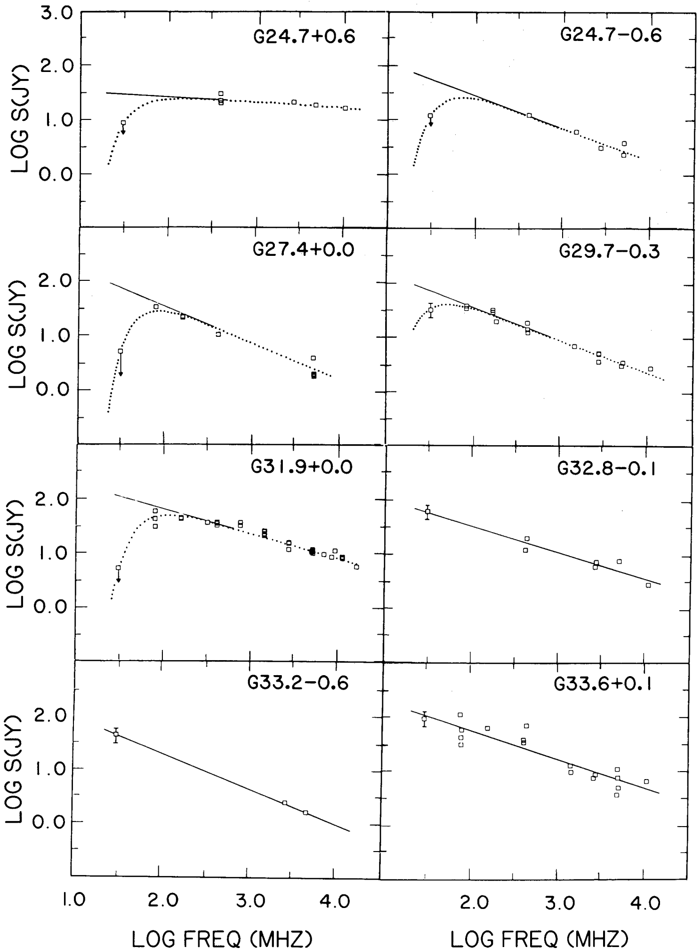

FIG. 1*c*

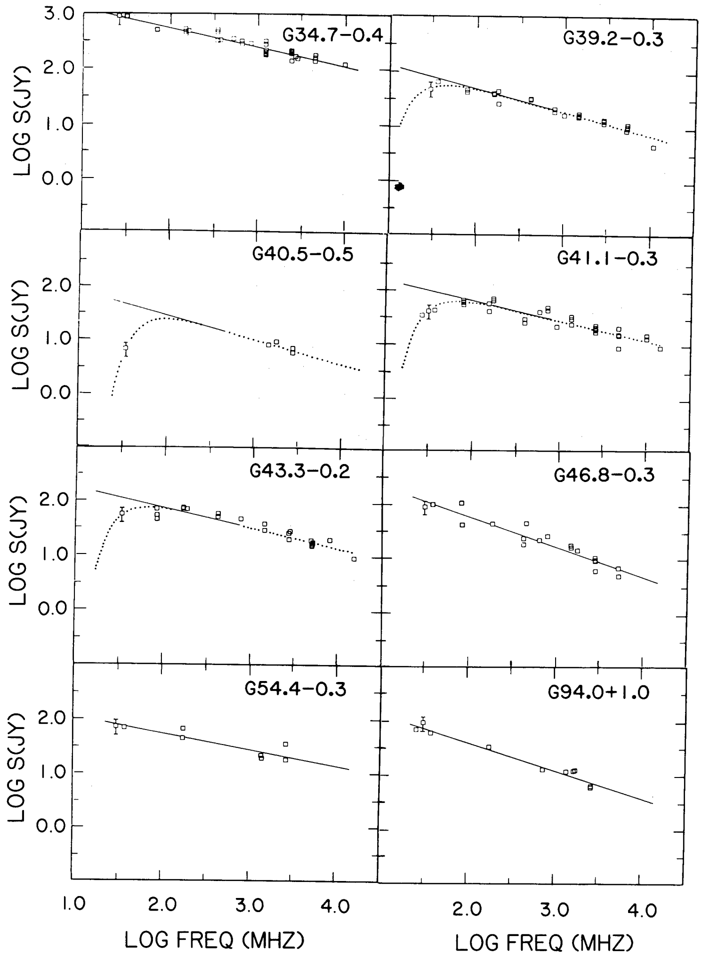

FIG. 1*d*

Finally, this assumption has been used previously to explain successfully the relatively high-frequency (≥ 100 MHz) turnovers of the SNRs W49 and 3C 391 and the powerful Galactic center source Sgr A East (Holden and Caswell 1969; Caswell *et al.* 1971; Dulk and Slee 1972).

b) *Upper Limit to the Electron Density of the WIM*

The assumption of intrinsically constant SNR spectral indices appears valid so that low-frequency spectral turnovers provide powerful probes of low-density, ionized gas in the ISM. However, the lack of high-resolution, low-frequency observations has meant that this technique has been relatively little used. As discussed above, the pioneering work of Dulk and Slee (1972, 1975) was hampered by the nearness of most turnovers to their lowest observing frequency (80 MHz). Our new measurements at low frequencies greatly improve upon their results.

The free-free optical depth, τ, is related to the emission measure, EM (cm^{-6} pc^{-1}), and electron temperature, T_e(K), of the intervening ionized gas (from Dulk and Slee 1975) by

$$\tau = 1.643 \times 10^5 a(T_e, \nu)(\nu^{-2.1})(\mathrm{EM}\ T_e^{-1.35}) , \qquad (2)$$

where a is the Gaunt factor[3], and ν is the continuum observing frequency measured in MHz. The emission measure EM is defined as

$$\mathrm{EM} = \int_L n^2 \, dl , \qquad (3)$$

where n is the thermal electron density in cm^{-3} and the integral is taken along the entire path length L in parsecs.

Although distances to SNRs are notoriously inaccurate, estimates are available from Green (1984) for a number of the objects in our survey. For convenience, we list these in Table 3 along with Green's evaluation of the accuracy of each.

It is important to note that such SNRs as G349.7+0.2 and G33.6+0.1 are very distant (see Table 3) but show no low-frequency turnovers (Fig. 1). This places severe constraints on the thermal electron density (n_e) of any widely distributed, ionized medium such as the WIM if its electron temperature (T_e) is taken to be $\sim$3000–8000 K, as estimated by Kulkarni and Heiles (1987). For example, using the 57.5 MHz observations which indicate $\tau_{57.5} \ll 1$ toward G349.7+0.2, the farthest (18.3 ± 4.6 kpc) observed SNR with a "good" distance estimate, equations (2) and (3) place an upper limit of $n_e \leq 0.26$ cm^{-3} for any WIM with a temperature of $T_e = 8000$ K or $n_e \leq 0.13$ cm^{-3} if $T_e = 3000$ K (because n_e^2 scales as $T_e^{1.35}$, and we have used $\tau_{57.5} \leq 0.2$ as an approximation of $\tau_{57.5} \ll 1$).

[3] For the range of astrophysical quantities with which we are concerned, the Gaunt factor $a(T_e, \nu) \sim 1$ can be assumed.

TABLE 2

CLARK LAKE OPTICAL DEPTHS TOWARD 51 GALACTIC SNRs

Source (1)	$\tau_{30.9}$[a] Clark Lake (2)	$\tau_{30.9}$[a] Culgoora (3)	α (4)	S_{408} (Jy) (5)	Type (6)
G348.5+0.1[b]	≤0.7	4.2 ± 1.3	0.3	94	S
G348.7+0.3[b]	≤0.7	1.7 ± 2.7	0.3	34	S
G349.7+0.2[c]	≤0.7	4.0 ± 1.9	0.3	25	S?
G350.1−0.3[c]	≤0.7	...	0.8	16	?
G355.9−2.5[c]	1.1 ± 0.2	...	0.5	12	S
G0.0+0.0[b]	≫1	≫1	0.8?	205?	S
G0.9+0.1[b]	≤1.5	...	?	?	C
G1.05−0.1[b]	≤1.5	...	?	?	?
G5.4−1.2[b]	≤0.2	...	0.2?	42?	C?
G6.4−0.1[c]	0.9 ± 0.3	...	0.4	424	C
G8.7−0.1[b]	≥1.8	...	0.25	113	S?
G9.8+0.6[c]	≥8.0	...	0.8	5.8	S
G10.0−0.3[c]	≥3.9	...	0.5	3.1	S?
G11.2−0.3[c]	2.1 ± 0.3	0.66 ± 2.8	0.5	30	S
G11.4−0.1[c]	3.7 ± 0.8	...	0.4	7.1	S
G12.0−0.1[c]	≤0.2	...	0.8	7.5	?
G15.9+0.2[c]	2.1 ± 0.3	...	0.7	8.5	S?
G18.8+0.3[c]	0.6 ± 0.3	...	0.5	49	S
G21.5−0.9[c]	≤0.2	...	0.0	7.2	P
G21.8−0.6[c]	0.9 ± 0.3	...	0.5	95	S
G22.7−0.2[c]	3.5 ± 0.9	...	0.2	65	S
G23.3−0.3[c]	7.2 ± 0.8	...	0.4	119	S
G23.6+0.3[c]	≥5.3	...	0.1	10	?
G24.7+0.6[c]	≥1.0	...	0.1	21	C?
G24.7−0.6[c]	≥1.6	...	0.6	12	S
G27.4+0.0[c]	≥2.8	2.1 ± 4.1	0.7	13	S
G29.7−0.3[c]	0.8 ± 0.2	1.8 ± 1.8	0.6	15	C
G31.9+0.0[c]	≥3.2	3.4 ± 1.8	0.5	33	S
G32.8−0.1[c]	≤0.2	...	0.5	17	S
G33.2−0.6[c]	≤0.2	...	0.6	8.5	S
G33.6+0.1[c]	≤0.2	4.0 ± 2.4	0.5	27	S
G34.7−0.4[c]	≤0.2	...	0.4	325	S
G39.2−0.3[c]	0.5 ± 0.2	0.2 ± 0.7	0.4	25	S
G40.5−0.5[c]	2.1 ± 0.3	...	0.5	16	S
G41.1−0.3[c]	0.9 ± 0.3	0.9 ± 0.4	0.4	39	S
G43.3−0.2[c]	0.9 ± 0.3	3.2 ± 0.7	0.4	46	S
G46.8−0.3[c]	≤0.2	...	0.6	29	S
G54.4−0.3[c]	≤0.2	...	0.3	36	S
G74.0−8.5[b]	≤0.3	...	?	?	S
G89.0+4.7[b]	≤0.3	...	0.4	315	S
G94.0+1.0[c]	≤0.1	...	0.5	21	S
G111.7−2.1[b]	≤0.1	...	0.77	5425	S
G130.7+3.1[b]	≤0.7	...	0.10	36	P
G160.9+2.6[b]	≤0.1	...	0.6	188	S
G184.6−5.8[b]	≤0.1	...	0.3	1361	P
G189.1+3.0[b]	≤0.1	...	0.36	221	S
G206.9+2.3[b]	1.1 ± 0.5	...	0.5	9.4	S?
G260.4−3.4[b]	≤0.1	...	0.5	204	S

[a] The Culgoora optical depths measured at 80 MHz and the Clark Lake optical depths measured at 57.5 MHz have been scaled to 30.9 MHz. (See eq. [2] in text.)

[b] No spectrum derived, all parameters except optical depths are taken from Green 1984, 1988 if available.

[c] Full spectrum is plotted in Fig. 1.

These low limits, while stringent, do not necessarily contradict the results of Reynolds (1988, and references therein), because gas with $n_e \sim 0.1$ cm^{-3} can still account satisfactorily for the widely distributed Hα emission attributed to the WIM without causing significant absorption at 30.9 or 57.5 MHz.

The fact that even some distant SNRs show no spectral turnover while some closer SNRs show considerable absorption demonstrates that the low-frequency absorbing medium is localized, patchy, and not due to a widely distributed ISM component like the WIM. This situation is illustrated in Figure 2, which shows a plot of optical depth versus distance for 15 SNRs within 100 pc of the Galactic plane with distance estimates listed in Table 3. There is no obvious correlation between $\tau_{30.9}$ and distance, as might be expected from absorption by a widely distributed, homogeneous medium.

For most SNRs, there is no evidence from centimeter-wavelength surveys for normal H II regions superposed along the line of sight except for a few well-known cases such as 3C 391, W49B, and Sgr A East, where higher frequency turnovers are present. Therefore, we postulate the existence of an

TABLE 3

DISTANCE ESTIMATES FOR 15 SNRs IN THE CLARK LAKE SAMPLE WITH $z \leq 100$ PARSECS[a]

Source	Distance (kpc)	Reliability
G348.5+0.1	10.4	Good
G348.7+0.8	10.4	Good
G349.7+0.2	18.3	Good
G357.7−0.1	≥6.0	Poor
G11.2−0.3	7.5	Poor
G18.8+0.3	14.0	Reasonable
G21.8−0.6	≥6.3	Poor
G31.9+0.0	11.0	Poor
G33.6+0.1	≥7.0	Poor
G34.7−0.4	3.0	Good
G41.1−0.3	≥7.5	Good
G43.3−0.2	10.0	Reasonable
G111.7−2.1	2.8	Good
G130.7+3.1	2.6	Good
G160.4+2.8	2.0	Good

[1] Distances and estimates of their reliability have been taken from Green 1984, who gives a detailed discussion of SNR statistics.

intermediate ISM component, more extended than normal H II regions but more localized than a broad Galactic distribution, which is responsible for the observed low-frequency absorption. This we call EHE, for extended H II envelopes, and we suggest that it could be the same gas of density $n \sim 0.5$–10.0 cm^{-3} and $T_e \sim 3000$–8000 K, which is assumed to be associated with, although more extended than, discrete H II regions and is thought to be the origin of 325 MHz recombination lines (A85*b*, A86).

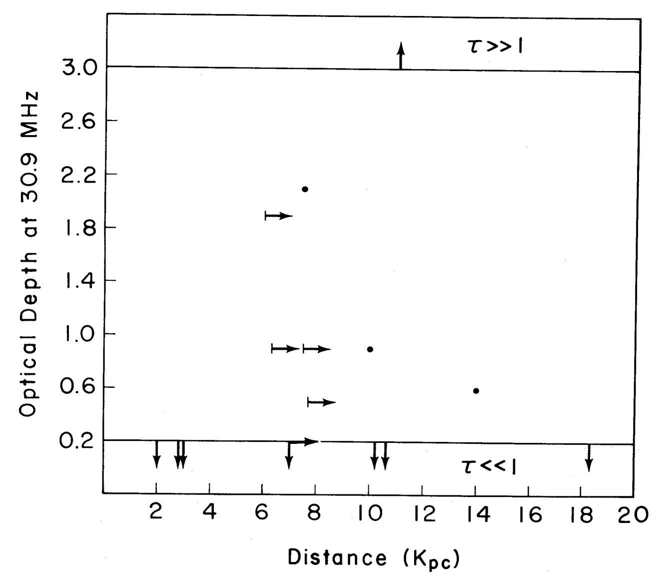

FIG. 2.—Plot of 30.9 MHz optical depth ($\tau_{30.9}$) against distance for 15 SNRs within 100 pc of the Galactic plane. Distance estimates are from Green (1984) and are listed in Table 3. There is no clear increase in absorption with distance, implying the absorption toward SNRs is patchy and not widely distributed. Lack of absorption toward distant SNRs constrains the properties of any distributed warm ionized medium (WIM) component of the ISM (see text). Where only limits on the distance or optical depth are available, they are indicated by arrows.

c) Evidence for the Existence of Extended H II *Envelopes (EHEs) around* H II *Regions*

In Table 4, we compare the optical depths scaled to 30.9 MHz toward nine SNRs derived from the Ooty recombination line observations with those obtained from Clark Lake continuum measurements. The Ooty optical depths have been calculated for both $T_e = 3000$ K and $T_e = 8000$ K, extremes of the possible electron temperatures constrained by observations of the 325 MHz line studies (A85*b*, A86). As can be seen, the CLRO and Ooty estimates of $\tau_{30.9}$ generally agree well, especially considering that the fan beam (size $\sim 2° \times 6'$) of the Ooty telescope samples a much larger region of the ISM than the region sampled by the smaller Clark Lake beam (size $\sim 15'$).

This comparison suggests that the same gas could account for both the 325 MHz recombination line emission and the patchy absorption of the low-frequency continuum emission from Galactic SNRs.[4] Unfortunately, the resolution of the Clark Lake survey and the surface brightness limitation of the Galactic recombination line surveys is insufficient to specifically connect absorption toward SNRs, most with unknown distances, to envelopes of identifiable H II regions. Anantharamaiah (1986) has estimated that the number of H II regions which lie toward the inner ($l \leq 40°$) Galaxy is such that every line of sight will eventually intersect a low-density EHE of average size 100 pc. However, it is still true that not all SNRs in the inner Galaxy will show low-frequency turnovers, since only foreground envelopes will produce absorption and there is likely to be a range of envelope sizes.

Additional evidence that the low-frequency continuum absorbing gas could be the same as the 325 MHz recombination line-emitting gas is provided by estimates of the thermal electron density. Using optical depths from the SNRs in our sample showing low-frequency turnovers, accepting a range of electron temperatures, and assuming a path length of 100 pc equal to that estimated by Anantharamaiah (1986), we derive an electron density of $n_e \sim 2.9$ cm^{-3} for $T_e = 3000$ K or $n_e \sim 5.7$ cm^{-3} if $T_e = 8000$ K. These values lie well within the Ooty

[4] This gas could also account for higher density clumps seen in Hα emission surveys. The density of these Hα clumps is estimated to be ~ 0.3 cm^{-3} with sizes ~ 100 pc if they are at their kinematic distance. Such sizes are also consistent with the path lengths derived from the Ooty data. See Reynolds (1983) for a more detailed discussion.

TABLE 4

CLARK LAKE AND OOTY OPTICAL DEPTHS[a] TOWARD NINE SNRs

SNR	$\tau_{30.9}$ Ooty[b] $T_e = 3000$ K	$\tau_{30.9}$ Ooty[b] $T_e = 8000$ K	$\tau_{30.9}$ CLRO
G357.7−0.1	1.8	0.5	1.9 ± 0.3
G6.6−0.1	3.2	0.9	0.9 ± 0.3
G11.2−0.3	2.2	0.6	2.1 ± 0.3
G21.8−0.6	2.6	0.7	0.9 ± 0.3
G23.0−0.2	5.0	1.3	⩾1
G31.9+0.0	3.0	0.8	⩾1
G34.7−0.4	1.0	0.3	≤0.2
G39.2−0.3	0.8	0.2	0.5 ± 0.2
G43.2−0.1	2.4	0.6	0.9 ± 0.3

[a] As in Table 2, all optical depths have been scaled to 30.9 MHz.

[b] Only a range of possible electron temperatures was constrained from the results presented in Anantharamaiah 1985*b*, 1986. Therefore, we have calculated here optical depths for the extremes of that range.

range of derived densities of 0.5–10.0 cm^{-3}. This check is valid, since electron densities derived in A85*b* and A86 were constrained by parameters independent of electron temperatures and path lengths.[5]

A crude estimate of the volume filling factor (VFF) of EHEs with radii R_{EHE} within the solar circle can be made if we model the inner Galaxy as a disk of radius $R_0 \sim 10$ kpc. This relates the EHE surface area filling factor (SFF) to the VFF by VFF $\sim$ SFF R_{EHE}/R_0. Since we measure SFF to be $\sim \frac{2}{3}$ (i.e., roughly two-thirds of SNRs toward the inner Galaxy show low-frequency absorption), this gives VFF $\sim \leq 1\%$. This order-of-magnitude estimate, while not fully independent from the Ooty results which use the same assumed $R_{EHE} \sim 100$ pc, is in good agreement with the 325 MHz recombination line derived VFF of $\sim \leq 1\%$ (A86), again suggesting the likelihood that they are the same ISM component. Such a small VFF indicates that this gas does not occupy a substantial fraction of the ISM.

Although there appears to be reasonably strong evidence for equating the low-frequency continuum-absorbing gas to the low-frequency recombination line emitting gas and placing it near H II regions in EHEs, it must be kept in mind that other models can explain our observed spectral turnovers:

1. Although it does not appear from the currently available centimeter-wavelength surveys that normal H II regions are frequent enough to account for the low-frequency absorption, absorption by relatively small, difficult to detect, high-density H II regions (or planetary nebulae) lying near to or along the line of sight and partially covering the surface of the SNR (as has been found to be at least partially the case in W30; Kassim and Weiler 1989) could produce the observed effect. The resolution of the Clark Lake survey and the resolution and surface brightness sensitivity limits of surveys used to identify H II regions (and SNRs) are insufficient to rule out this possibility. However, such compact H II regions could not explain the low-frequency recombination line results.

2. The existence of cold, partially ionized clouds with $T_e \sim 100$ K, $n_e \sim 0.3$ cm^{-3}, and size ~ 100 pc would also account for the Clark Lake results. However, such a gas would not produce the low-frequency recombination lines, and there is no other evidence for its existence. Thus we feel that, based on evidence available at present, the most likely absorbing ISM component is a distribution of extended H II envelopes (EHEs) around H II regions. It should be kept in mind, however, that we have presented no evidence here specifically linking EHE gas to normal H II regions, because this important conclusion is based solely on the agreement between the velocities of high- and low-density line-emitting regions (A86).

d) Constraints on Low-Frequency Absorbing Gas in the Outer Galaxy

Since most SNRs in our sample are located toward the inner Galaxy, our results place relatively fewer constraints on the distribution of ionized gas in the outer Galaxy. However, source counts based upon results of our 30.9 MHz survey toward the outer Galaxy ($132° \leq 1 \leq 251°$) are consistent with those expected from an extrapolation of extragalactic source counts at higher frequencies (K87, K88*b*).[6] This implies that there is little ionized gas in the outer Galaxy similar to the component in the inner Galaxy responsible for our observed SNR spectral turnovers. This result is also generally consistent with the absorbing gas being associated with individual H II regions since few are located in the outer Galaxy. An exception is the region near $l = 224°$ where there is a large H II complex known as S296. In fact, this region does show a decrement in the 30.9 MHz outer Galaxy ($132° \leq 1 \leq 250°$) source counts (K87).

A 13 cm radio map of S269 is reproduced in Figure 3 from Gaylard and Kemball (1984), who conclude from continuum and recombination line observations that the emission is predominantly thermal. If a distance of 1150 pc is assumed (Claria 1974*a*, *b*) for S296, the extended region of emission is approximately 100 pc EW by 140 pc NS, roughly the size of the postulated EHE. Gaylard and Kemball (1984) derive an electron temperature of 6900 ± 1300 K, and measurements of the emission measure (EM) for the region indicate an electron density with a range of $n_e \sim 1$–10 cm^{-3}, depending on the clumpiness of the distribution.

Kassim (1987) has shown that such properties could easily account for the 30.9 MHz source count decrement in that direction, although his result is only a suggestion which needs to be confirmed by further observations, preferably at multiple frequencies. It is interesting to note that the parameters for the extended envelope of S296 are typical of the values needed for the EHE discussed above (see § IV*c*). Such extended envelopes would go undetected on maps similar to Figure 3 made toward H II regions in the inner Galaxy because of confusion, limited instrument dynamic range, and the strong contribution from the Galactic background. Reynolds (1988), in fact, has suggested that mapping thermal sources at high Galactic latitudes may be another means of delineating and determining the properties of extended H II region envelopes.

V. CONCLUSIONS

Accurate low-frequency radio continuum spectra for 32 Galactic SNRs located mainly toward the inner Galaxy have been obtained using observations made with the Clark Lake TPT telescope. Of these, approximately two-thirds show turnovers at low frequencies implying the presence of a common, but inhomogeneously distributed, ionized absorbing medium along the lines of sight. These spectra have been combined with other Clark Lake observations to derive free-free optical depths toward a total of 47 Galactic SNRs. An analysis of these results indicates:

1. In the absence of absorbing gas along the line of sight, SNR spectral indices are intrinsically constant to dekametric wavelengths.

2. The absorbing gas present in the Galactic plane is patchy.

3. Any widely distributed warm ionized medium (WIM) must have $n_e \leq 0.26$ cm^{-3} if $T_e \sim 8000$ K, or $n_e \leq 0.13$ cm^{-3} if $T_e \sim 3000$ K. These limits for the WIM, however, do not contradict limits established by Reynolds (1983) indicating $n_e \sim \leq 0.1$ cm^{-3}.

4. The low-frequency absorbing gas has properties which

[5] The electron densities n_e were derived exclusively from recombination line observations, while the electron temperature and path length estimates were constrained by high-frequency continuum observations, the average electron density in the ISM, and the geometry of the line-emitting regions.

[6] Source counts from the Clark Lake survey (K87, K88*a*, *b*) toward the outer Galaxy indicate 2.1×10^3 sources per steradian stronger than 4 Jy at 30.9 MHz, while source counts based on the results of the 5C, 5C2, and Molongolo surveys (Pearson 1975) and using $\alpha = -0.75$ predict 2.2×10^3 sources per steradian greater than 4 Jy at 30.9 MHz.

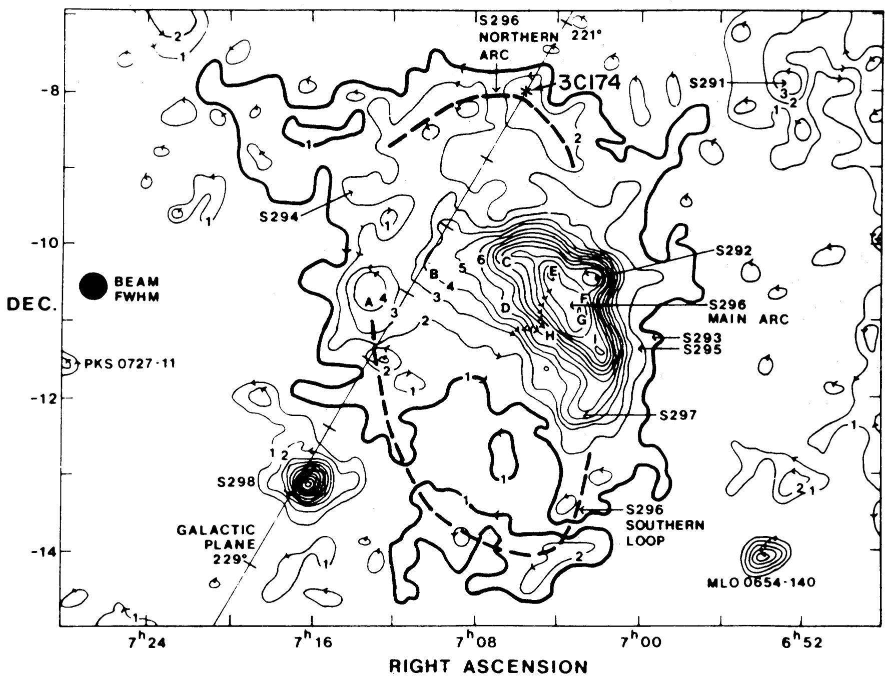

FIG. 3.—2272 MHz total intensity contour map of the S296 H II complex (Gaylard and Kemball 1984). Contour interval is in steps of 30 mK antenna temperature above the adopted zero level. Low-level extended emission shown in this map is direct evidence for a low-density ionized halo associated with S296. Such a halo would be undetectable toward the inner Galaxy due to confusion, limited instrument dynamic range, and a high contribution from the Galactic background.

are consistent with those of extended H II envelopes (EHEs) surrounding classical H II regions as postulated by Anantharamaiah (1986) to explain his 325 MHz recombination line survey results; i.e., $T_e \sim 3000$–8000 K, $n_e \sim 0.5$–10 cm^{-3}, sizes ~ 50–200 pc, and Galactic filling factor $\sim < 1\%$. However, direct observational evidence linking EHE to normal H II regions is still lacking except for the recombination line results.

It must be noted that our observations cannot rule out an origin for the observed low-frequency absorption by small, normal H II regions (or planetary nebulae) along the lines of sight to the SNRs or absorption by widely distributed, cold, partly ionized clouds. Neither of these last two possibilities, however, can account for the 325 MHz recombination line data. New tests for the existence of EHEs can be carried out best by (1) deep mapping of H II regions at high Galactic latitudes or in the outer Galaxy where EHEs may be detectable in emission; (2) further meter wavelength recombination line observations which are sensitive to the stimulated emission which can only arise from EHE low-density, hot, ionized gas; and (3) higher resolution ($< 10'$) dekameter continuum observations combined with higher surface brightness sensitivity centimeter wavelength recombination line observations which can study the possibility that the low-frequency absorption originates in compact H II regions along the line of sight.

The author would like to thank William C. Erickson for suggesting the project and Kurt W. Weiler for many useful discussions and comments. The Clark Lake Radio Observatory was supported by the National Science Foundation under grant AST-8416179. Part of this work was taken from a thesis submitted in partial fulfillment of the requirements for the Ph.D. degree in the department of Physics and Astronomy at the University of Maryland.

REFERENCES

Anantharamaiah, K. R. 1985*a*, *J. Ap. Astr.*, **6**, 177 (A85*a*).
———. 1985*b*, *J. Ap. Astr.*, **6**, 203 (A85*b*).
———. 1986, *J. Ap. Astr.*, **7**, 131 (A86).
Baars, J. W. M., Genzel, R., Pauliny-Toth, I. I. K., and Witzel, A. 1977, *Astr. Ap.*, **61**, 99.
Caswell, J. L., Dulk, G. A., Goss, W. M., Radhakrishnan, V., and Green, A. J. 1971, *Astr. Ap.*, **12**, 271.
Claria, J. J. 1974*a*, *A.J.*, **79**, 1022.
———. 1974*b*, *Astr. Ap.*, **37**, 229.
Downes, D., Goss, W. M., Schwarz, U. J., and Wouterloot, J. G. A. 1978, *Astr. Ap. Suppl.*, **35**, 1.
Dulk, G. A., and Slee, O. B. 1972, *Australian J. Phys.*, **25**, 429.
———. 1975, *Ap. J.*, **199**, 61.
Erickson, W. C., and Mahoney, M. J. 1985, *Ap. J.*, **290**, 596.
Erickson, W. C., Mahoney, M. J., and Erb, K. 1982, *Ap. J. Suppl.*, **50**, 403.
Gaylard, M. J., and Kemball, A. J. 1984, *M.N.R.A.S.*, **211**, 155.
Gottesman, S. T., and Gordon, M. A. 1970, *Ap. J.* (*Letters*), **162**, L93.
Green, D. A. 1984, *M.N.R.A.S.*, **209**, 449.
———. 1988, *Ap. Space Sci.*, **148**, 3.
Hart, L., and Pedlar, A. 1976, *M.N.R.A.S.*, **176**, 547.
Holden, D. J., and Caswell, J. L. 1969, *M.N.R.A.S.*, **143**, 407.
Jackson, P. D., Kassim, N. E., and Kundu, M. R. 1985, *Bull. AAS*, **17**, 545.
Jackson, P. D., and Kerr, F. J. 1975, *Ap. J.*, **196**, 723.
Kassim, N. E. 1987, Ph.D. thesis, University of Maryland.
———. 1988*a*, *Ap. J. Suppl.*, **68**, 715 (K88*a*).
———. 1988*b*, *Ap. J.* (*Letters*), **328**, L55 (K88*b*).
———. 1989, *Ap. J. Suppl.*, **71**, in press.
Kassim, N. E., Erickson, W. C., and LaRosa, T. N. 1986, *Nature*, **322**, 522.
Kassim, N. E., and Weiler, K. W. 1989, in preparation.
Kassim, N. E., Weiler, K. W., and Baum, S. A. 1989, *Ap. J.*, submitted.
Kassim, N. E., Weiler, K. W., Erickson, W. C., and Wilson, T. L. 1989, *Ap. J.*, **338**, 152.
Kulkarni, S. R., and Heiles, C. 1987, in *Interstellar Processes*, ed. D. J. Hollenbach and H. A. Thronson (Dordrecht: Reidel), p. 87.
LaRosa, T. N., and Kassim, N. E. 1985, *Ap. J.* (*Letters*), **299**, L13.
Lockman, F. J. 1976, *Ap. J.*, **209**, 42.
Mahoney, M. J. 1986, in *Low Frequency Radio Astronomy*, ed. W. C. Erickson and H. V. Cane (NRAO), p. 77.
Mahoney, M. J., and Kassim, N. E. 1985, *Bull. AAS*, **16**, 995.
Mathis, J. S. 1986, *Ap. J.*, **301**, 423.
Odegard, N. 1986*a*, *A.J.*, **92**, 1372.
———. 1986*b*, *Ap. J.*, **301**, 813.

Pearson, T. J. 1975, *M.N.R.A.S.*, **171**, 475.
Reynolds, R. J. 1983, *Ap. J.*, **268**, 698.
———. 1984, *Ap. J.*, **282**, 191.
———. 1988, *Ap. J.*, **333**, 341.
Reynolds, S. P., and Aller, H. D. 1985, *A.J.*, **90**, 2312.
Shaver, P. A. 1976, *Astr. Ap.*, **49**, 1.
Wilson, T. L. 1980, in *Radio Recombination Lines*, ed. P. A. Shaver (Dordrecht: Reidel), p. 205.

NAMIR E. KASSIM: Code 4131-K, Naval Research Laboratory, Washington, DC 20375-5000